The Effect of Hybrid Drying Methods on the Quality of Dried Carrot

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Abstract: The study investigated the effect of a combination of drying techniques: convection, microwave, and freeze-drying, on selected physical properties of the dried material (carrot) to determine which form of hybrid drying is the best alternative to traditional freeze-drying. Carrots were dried by freeze-drying, convection-drying, and microwave-drying as well as in hybrid methods: freeze-drying-convection, freeze-drying–microwave as well as convection–freeze-drying or microwave–freeze-drying. The color, porosity, shrinkage, water activity, dry matter content, and internal structure of carrots dried using various methods were examined. The dried samples obtained with the hybrid method were compared with those obtained with a single drying technique. Freeze-drying–microwave-drying (F-M) as an alternative drying method for freeze-drying allowed us to obtain dried material with a water activity similar (p < 0.05) to that of freeze-dried samples, at the same time reducing the duration of the process by 20 h. The combination of convection-drying methods with freeze-drying (K-F) and microwave-drying with freeze-drying (M-F) allowed us to obtain dried material with lower shrinkage than in the case of convection (K) or microwave (M) drying.

Keywords: carrots; convective-drying; freeze-drying; hybrid drying methods; microwave-drying

1. Introductions

Carrots are a vegetable with a pleasant, sweet taste [1]. The only edible part of the carrot is the conical storage root, which is a source of valuable nutrients. The root of garden carrots is orange, red, or purple, depending on the amount of the pigment (β-carotene) [2]. Fresh carrot root consists of 88% water, 10% carbohydrates, and 2% protein with minerals and vitamins. It also contains calcium, phosphorus, potassium, sodium, magnesium, iron, cobalt, zinc, and vitamins, mainly: A, B1, B2, B6, PP, and folic acid [3].

Most of the production of this vegetable is directed at processing, including drying. An important direction of using dried carrots is mixtures of dried spices used in the preparation of meals. In the era of the developing “fit” and “eco” food trends, dried carrots are also used as a snack for quick consumption, e.g., carrot chips [4]. The reduced amount of water in the material lowers its activity, contributing to the prevention of the development of microorganisms [5], and the products can be stored for a long time without visible signs of deterioration [6]. Moreover, enzymatic and non-enzymatic transformations are reduced [7].

The most commonly used method of drying food is convection heating, which uses air, which is also a factor that supplies heat and removes water from the material [8]. The most important parameter in convection-drying is the temperature, the increase of which causes the acceleration of the drying process. Convection-drying is used to preserve fruit, vegetables, and meat, but high temperature and long process time adversely affect the quality of the obtained products (reduced nutritional value, changes in color, smell,
Other popular drying methods are freeze-drying, fluidization, and combined (hybrid) methods [11]. Microwave-drying in the food industry uses waves in the 2450 and 915 MHz frequency range. Microwaves interact with the water dipoles of the dried material, due to which hydrogen bonds are broken and energy is released in the form of heat through molecular friction [12]. Due to the high microwave permeability, the product is fully heated with a simultaneous temperature increase [13]. Microwave-drying shortens the processing time, intensifies heat and mass transfer, and lowers costs. It is an alternative to conventional drying methods for a wide range of food products with high water content, such as potatoes, carrots, apples, bananas, and parsley [14]. In addition, it allows the attractive color of products to be maintained and reduces the loss of bioactive ingredients [15].

Freeze-drying is a method that removes water from a previously frozen material by sublimation of ice, omitting the liquid phase [16]. Usually, it takes 24–48 h [17]. Freeze-dried samples are characterized by a porous structure, and preservation of the smell and color of the raw material. The chemical composition of the freeze-dried material slightly changes, especially when it comes to vitamins, micro and macro elements [18]. The disadvantage of the process is the high costs related to the duration and complex apparatus, therefore alternative drying methods are sought to maintain the high quality of the product [19].

Researchers have started to investigate the potential of combining more than one drying technique. This has led to the development of hybrid drying technologies [20]. Combined (hybrid) drying is a method of combining simple drying techniques into one complex process, e.g., convection, microwave, freeze-drying, and ultrasound. The number of drying methods used in combination is not specified [21,22]. The technology of combining several drying methods is relatively new, constantly improving and developing. The techniques used during combined drying concern: the method of heat transfer, multistage, and multi-process drying, and using other treatments in addition to drying, e.g., filtration, and agglomeration. The following is a breakdown of combined drying methods (Figure 1) [23].

Such a solution reduces the time and increases the rate of water removal from the material, thanks to which the raw material is not exposed to long-term high temperatures, thus preserving its nutritional value, color, and structure [24]. Rząca and Witrowa-Rajchert [11], examining the process of drying apples with the use of combined drying methods, showed that the use of convection and microwave-drying had a positive effect on the quality of the dried fruit and the duration of the process. The research conducted by Horuz et al. [25] confirmed the advantage of combined drying methods over traditional ones. The use of the combined microwave–convection method, compared to convection-drying, shortened the
drying time by half, reduced energy consumption, and allowed the researchers to obtain a higher vitamin content in cherries compared to convection-drying.

This study aimed to investigate how the combined drying methods affect the quality of dried carrots and to determine which of the tested drying techniques allows the obtaining of a dried product similar in quality to that of freeze-drying. The scope of the work included the selection of combined drying techniques, the determination of the parameters of the drying process, and the analysis of selected indicators of the quality of dried carrots.

2. Materials and Methods

2.1. Materials and Samples Preparation

The research material was carrots of the “Nantejska” variety, with an average length of 15 cm and an orange color. Carrots were cut in the form of discs with a diameter of 10 mm and a thickness of 5 mm. The material cut with the guillotine was blanched in boiling water for about 1 min to deactivate the enzymes, and then immersed in cold water. Then discs were blotted dry and dried. In the case of freeze-drying, the samples were previously frozen in a National Lab GmbH freezer (ProfiMaster Personal Freezers PMU series, Berlin, Germany) at −80 °C for 2 h.

2.1.1. Drying

The possibility of combining various drying techniques was investigated to develop a hybrid drying method that would allow obtaining of a high-quality product, similar to the quality of freeze-dried material while reducing the costs of the process. About 1 kg of carrots was used for every drying method. Carrots of uniform shape and color and similar size were used for drying. Drying was performed three times for each method. The following drying methods were used in the experiment: convection, microwave–convection, and freeze-drying in various combinations (Table 1).

Table 1. The types of samples dried, sample symbols, and process parameters.

<table>
<thead>
<tr>
<th>Drying Method</th>
<th>Sample Symbol</th>
<th>Parameters</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Convective-drying</td>
<td>K</td>
<td>40</td>
<td>-</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Microwave-drying</td>
<td>M</td>
<td>30</td>
<td>-</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>Freeze-drying</td>
<td>F</td>
<td>20</td>
<td>-</td>
<td>24</td>
<td></td>
</tr>
<tr>
<td>Freeze-drying–convection</td>
<td>F-K</td>
<td>20/40</td>
<td>2/4</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Freeze-drying–microwave</td>
<td>F-M</td>
<td>20/30</td>
<td>2/0.15</td>
<td>2.15</td>
<td></td>
</tr>
<tr>
<td>Convection–freeze-drying</td>
<td>K-F</td>
<td>40/20</td>
<td>2/12</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>Microwave–freeze-drying</td>
<td>M-F</td>
<td>30/20</td>
<td>0.12/11</td>
<td>11.12</td>
<td></td>
</tr>
</tbody>
</table>

2.1.2. Convection-Drying

Drying was carried out in a TA 100 laboratory dryer (Poland). Carrot rings were placed on a sieve in a single layer and dried at the temperature of 70 °C with airflow of 4 m/s in the direction parallel to the laid material. The drying process was carried out until the water content was approximately 5%. The process time was about 4 h. The change in material mass was recorded by using POMIAR software (DOSBox v0.74; Radwag, Toruń, Poland) connected to an A 5000 microprocessor scale from the AXIS company (Gdańsk, Poland). The drying process was repeated three times.

2.1.3. Microwave-Drying

The process of convection-drying with microwaves was supported. Drying was carried out in a PROMIS Tech laboratory dryer (Wrocław, Poland) with the possibility of controlling air temperature, and microwave power, and measuring changes in the mass and temperature of the material. The microwave power of 300 W and the air temperature of 40 °C were used during drying. Registration of the material mass change during drying...
was possible with the use of a B3 electronic scale by AXIS. The scale connected to the computer registered the mass changes in the PROMIS program (Poland), recording the course of microwave-drying. The microwaves were turned off during the temperature and mass measurement. Drying was carried out in triplicate, for about 0.5 h, until the water content of the material was about 5%.

2.1.4. Freeze-Drying

Frozen samples were freeze-dried at a pressure of 63 Pa and a safety pressure of 103 Pa, at a temperature of heating shelves at 10 °C for 24 h in a Christ ALPHA1-4 LDC-1 m freeze-dryer (Osterode am Harz, Germany). The material after freeze-drying was stored in tightly closed containers in a dark place, at room temperature 20 °C.

2.1.5. Freeze-Drying and Convection-Drying

The freeze-drying process was carried out at the pressure of 63 Pa and the safety pressure of 103 Pa, with the temperature of the heating shelves at 10 °C for about 2 h in the Christ ALPHA1-4 LDC-1 m freeze-dryer (Osterode am Harz, Germany), and then the samples were dried in a TA 100 convection dryer to a water content of about 5%. The material subjected to convection-drying was placed on a sieve in a single layer and dried at the temperature of 70 °C with an airflow of 4 m/s in the direction parallel to the laid material. The total duration of the hybrid drying process was about 6 h.

2.1.6. Freeze-Drying and Microwave-Drying

Before freeze-drying, the samples were frozen in the National Lab GmbH freezer (Profi-Master Personal Freezers PMU series, Berlin, Germany), and then the freeze-drying process was carried out at the pressure parameters of 63 Pa and a safety pressure of 103 Pa, with the temperature of the heating shelves at 10 °C for about 2 h in the Christ ALPHA1-4 LDC-1 m freeze-dryer (Germany). The samples were dried in the PROMIS Tech microwave-convection dryer at the microwave power of 300 W and a temperature of 40 °C until the water content in the dried material was about 5%. The duration of the process was about 2.15 h.

2.1.7. Convection-Drying and Freeze-Drying

Raw carrot discs were placed on a sieve in a single layer and dried at the temperature of 70 °C with an airflow of 4 m/s in the direction parallel to the laid material. The drying process was carried out until the water content was approximately 50%, and then the samples were placed in the National Lab GmbH (ProfiMaster Personal Freezers PMU series, Berlin, Germany) freezer at −80 °C for 2 h, and then placed in the Christ ALPHA1-4 LDC-1 m freeze dryer (Germany) to dry to a water content of about 5%. The duration of the process was approximately 14 h.

2.1.8. Microwave-Drying and Freeze-Drying

During drying in a PROMIS Tech drying oven, microwave power of 300 W and air temperature of 40 °C were used. The material was dried to a water content of about 50% for 12 min, and then the samples were placed in a National Lab GmbH (ProfiMaster Personal Freezers PMU series, Berlin, Germany) freezer at −80 °C for 2 h and freeze-dried in a Christ ALPHA1-4 LDC-1 m freeze dryer, to dry the material to a water content of about 5%. The duration of the process was approximately 11.12 h.

2.2. Analytical Methods

2.2.1. Dry Matter Content Determination

The dry matter content was determined by the standard PN-90/A-75101/03 in raw material and directly after drying, in three repetitions. Samples of raw and dried carrots were tested. Three slices of the research material were put into a weighing vessel of known weight and weighed on an analytical balance with an accuracy of 0.0001 g. Then uncovered weighing vessels with the tested material were dried for 24 h at a temperature
of about 65 °C in a SUP-65 W dryer by WAMED (Warsaw, Poland). After this time, the cells were placed in a desiccator for about 30 min to cool. The research material was weighed again [26].

2.2.2. Water Activity Determination

Measurement of water activity was performed using a Rotronic apparatus (Rotronic HygroLab C1, Bassersdorf, Switzerland), after 24 h of storage of the dried material from the moment of the completion of drying, to equalize the humidity in the material at the temperature of 25 °C. The process was carried out, according to the manufacturer’s instructions, in triplicate.

2.2.3. Color Determination

The color of the raw material and the dried material were measured using the Minolta Chromametr-300 apparatus (Japan) in the CIE L* a* b* system. The study was carried out with standard lighting in five repetitions. Based on the obtained data the absolute difference in color [ΔE] was calculated [27].

The absolute difference in color [ΔE]

\[ ΔE = \sqrt{(L^{*'} - L^*)^2 + (a^{*'} - a^*)^2 + (b^{*'} - b^*)^2} \]

where:
- \( L^* \) is the lightness/darkness coefficient
- \( a^* \) is the redness/greenness coefficient
- \( b^* \) is the yellowness/blueness coefficient
- \( ^* \) is coefficients of the raw carrot before drying.

2.2.4. Porosity Determination

The porosity of the dried material was measured using a Quantachrome Stereopycnometer helium pycnometer (Boynton Beach, FL, USA). Test material of known mass (m) and unknown volume (Vp) was introduced into a large measuring cell with a known volume (Vc). Then it was placed in the apparatus. The helium flowing through the sample filled all the gaps and pores between the dried discs, which made it possible to measure the volume of the tested sample. Each sample was washed three times with gas. The helium pycnometer determined the pressure values P1 and P2. After entering the obtained pressure values into the Pycnometer software version 2.7 computer program, the apparent density of the particles of the research material was determined [28].

2.2.5. Shrinkage Determination

The shrinkage was determined using the displacement method. Five slices of test material of known mass and unknown volume were placed in a cylinder of known volume. A burette of the same volume as the cylinder was filled with distilled water. Then the cylinder was filled up to the mark with water. The remaining water in the burette corresponded to the volume of 5 slices of the test material. Based on the material volume measurements, the shrinkage was determined, and additionally, the measurement of the mass of the samples made it possible to calculate the density. The same determination was made on dried carrots, but instead of water, sea sand was used for the elimination of water absorption by dried samples [28]. Two cylinders with the same volume were used. The five dried and weighed carrot slices were placed in one cylinder. Sea sand was poured onto the samples from the second cylinder until the higher meniscus of the solid reached a value equal to the first cylinder volume.

2.2.6. Structure Determination

The structure of the dried carrots was investigated based on photos made with the use of a TM-3000 HITACHI scanning electron microscope at 100× magnification [29]. From the
middle part of the dried carrot discs, a piece of ~1 mm of thickness was cut out along their axis by a razor blade.

2.2.7. Statistical Analysis

The mathematical elaboration of the results was prepared using the computer program Excel. The results were statistically analyzed using the analysis of variance based on the ANOVA summary table (StatSoft–Statistica 13.1), adopted level of significance \( p < 0.05 \).

3. Results

The relationship between the drying method and the water activity (\( a_w \)) parameter was assessed. As a result of the research, the average content of water activity of dried carrots was shown in Figure 2. The lowest value of the examined parameter was characteristic of freeze-dried carrot (F), the water activity of which was 0.176. In turn, the dried material obtained as a result of microwave (M) and convection (K) drying was characterized by the highest water activity, respectively, \( a_w = 0.390 \) and \( a_w = 0.300 \), and the differences are statistically significant (Table 2). The combination of freeze-drying with convection-drying (F-K (freeze-drying–convection), K-F (convection–freeze-drying)) and microwave-drying (F-M (freeze-drying–microwave), M-F (microwave–freeze-drying)) results in obtaining water activity with a much higher value and statistically significant difference than in the case of freeze-drying (F). An intermediate \( a_w \) value was obtained for samples from drying, where the first freeze-drying method (F-K, F-M) was used, the duration of which was much shorter than that of the freeze-drying process.

![Figure 2](image-url)

**Figure 2.** The impact of the type of drying method on the water activity of dried carrots. The same letters (a–e) in individual columns indicate the absence of a statistically significant difference between the samples (significance level 0.05). Designations in Table 1.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Count</th>
<th>Average</th>
<th>Standard Deviation</th>
<th>Coeff. of Variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>K-F</td>
<td>3</td>
<td>0.329333</td>
<td>0.00321455</td>
<td>0.976078%</td>
</tr>
<tr>
<td>K</td>
<td>3</td>
<td>0.299667</td>
<td>0.0023094</td>
<td>0.770657%</td>
</tr>
<tr>
<td>F-M</td>
<td>3</td>
<td>0.262</td>
<td>0.0043589</td>
<td>1.6637%</td>
</tr>
<tr>
<td>F</td>
<td>3</td>
<td>0.175667</td>
<td>0.0190351</td>
<td>10.8359%</td>
</tr>
<tr>
<td>F-K</td>
<td>3</td>
<td>0.335</td>
<td>0.0069282</td>
<td>2.06812%</td>
</tr>
<tr>
<td>M-F</td>
<td>3</td>
<td>0.312</td>
<td>0.0155242</td>
<td>4.9757%</td>
</tr>
<tr>
<td>M</td>
<td>3</td>
<td>0.39</td>
<td>0.00866025</td>
<td>2.22058%</td>
</tr>
</tbody>
</table>

The influence of the drying method on the dry matter content of dried carrots was also investigated (Figure 3) (Table 3). It was shown that all drying methods allowed us to obtain dried material with a dry substance content exceeding 94%. The highest value was observed for freeze-dried carrots (F)-98.36%. The dried material obtained by convection-drying (K)
was characterized by a dry matter content of 94.95%. The combination of freeze-drying with convection-drying allowed us to obtain dried samples with the following dry substance content: 95.68% (F-K), 94.11% (K-F), while in microwave-drying 96.47% (F-M), 94.47% (M-F), respectively. All these values of the dry matter content are lower than in the case of freeze-drying at 98.36% (F). On the other hand, combined drying methods using freeze-drying as the first technique (F-K; F-M) did not differ significantly in terms of dry matter content. The freeze-dried sample with microwave-drying (F-M) was characterized by a similar level of dry matter content to the control sample, which was freeze-dried (F). Carrot samples in which freeze-drying was used as a drying step (M-F, K-F) did not differ in the dry matter content.

Figure 3. The impact of the type of drying method on the dry matter content of dried carrots. The same letters (a–c) in individual columns indicate the absence of a statistically significant difference between the samples (significance level 0.05). Designations in Table 1.

Table 3. The results of the analysis of the variance of dry matter content for dried carrots depend on the drying method. Statistical significant differences at p < 0.05. Designations in Table 1.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Count</th>
<th>Average</th>
<th>Standard Deviation</th>
<th>Coeff. of Variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>K-F</td>
<td>3</td>
<td>94.1167</td>
<td>0.862863</td>
<td>0.916802%</td>
</tr>
<tr>
<td>K</td>
<td>3</td>
<td>94.1</td>
<td>1.30288</td>
<td>1.38457%</td>
</tr>
<tr>
<td>F-M</td>
<td>3</td>
<td>96.4667</td>
<td>0.297714</td>
<td>0.308618%</td>
</tr>
<tr>
<td>F</td>
<td>3</td>
<td>98.36</td>
<td>0.31</td>
<td>0.315169%</td>
</tr>
<tr>
<td>F-K</td>
<td>3</td>
<td>95.68</td>
<td>1.07791</td>
<td>1.12658%</td>
</tr>
<tr>
<td>M-F</td>
<td>3</td>
<td>94.4633</td>
<td>0.749689</td>
<td>0.793629%</td>
</tr>
<tr>
<td>M</td>
<td>3</td>
<td>95.3667</td>
<td>0.520416</td>
<td>0.545701%</td>
</tr>
</tbody>
</table>

Figure 4 shows the results of the apparent density of dried carrots for various drying methods. It was shown that the type of drying method used had a statistically significant effect on the apparent density of the material (Figure 4) (Table 4). The freeze-dried (F) carrot sample obtained the lowest density. The samples subjected to convection (K) and microwave (M) drying were characterized by the highest density. All samples using methods combined with freeze-drying (F-K, F-M, K-F, M-F) had a higher density value compared to the control sample (F), but lower than for convective dried (K) and microwave-dried (M).

The average values of shrinkage are presented in Figure 5. It was shown that the applied drying methods affected the material shrinkage. The highest value of shrinkage is characteristic of convection-dried carrots (K), for which this parameter is 68.95%. The dried material obtained by the methods of combined drying with the use of freeze-drying (F-K, F-M, K-F) was characterized by shrinkage with lower values not significantly different from each other (Table 5). The results ranged from 54.75–58.16%. The lowest shrinkage is characteristic for carrots subjected to combined drying (F-K) 54.75%. Between the results
of shrinkage for dried samples (F-M) 57.29% and (K-F) 58.16%, there was no statistically significant difference. Similar relationships were obtained between samples freeze-dried (F) 60.35% and microwave–freeze-dried (M-F) 61.06%, for which the obtained results do not differ statistically significantly.

**Figure 4.** The impact of the type of drying method on the apparent density of dried carrots. The same letters (a–g) in individual columns indicate the absence of a statistically significant difference between the samples (significance level 0.05). Designations in Table 1.

**Table 4.** The results of the analysis of the variance of apparent density for dried carrots depend on the drying method. Statistical significant differences at $p < 0.05$. Designations in Table 1.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Count</th>
<th>Average</th>
<th>Standard Deviation</th>
<th>Coeff. of Variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>K-F</td>
<td>3</td>
<td>0.73</td>
<td>0.01</td>
<td>1.36986%</td>
</tr>
<tr>
<td>K</td>
<td>3</td>
<td>0.868333</td>
<td>0.00763763</td>
<td>0.879573%</td>
</tr>
<tr>
<td>F-M</td>
<td>3</td>
<td>0.415667</td>
<td>0.00057735</td>
<td>0.138897%</td>
</tr>
<tr>
<td>F</td>
<td>3</td>
<td>0.183333</td>
<td>0.0057735</td>
<td>3.14918%</td>
</tr>
<tr>
<td>F-K</td>
<td>3</td>
<td>0.556667</td>
<td>0.0057735</td>
<td>1.03716%</td>
</tr>
<tr>
<td>M-F</td>
<td>3</td>
<td>0.513667</td>
<td>0.00507977</td>
<td>1.07221%</td>
</tr>
<tr>
<td>M</td>
<td>3</td>
<td>0.81</td>
<td>0.0</td>
<td>0%</td>
</tr>
</tbody>
</table>

**Figure 5.** The impact of the type of drying method on the shrinkage of dried carrots. The same letters (a–d) in individual columns indicate the absence of a statistically significant difference between the samples (significance level 0.05). Designations in Table 1.
Table 5. The results of the analysis of the variance of shrinkage for dried carrots depend on the drying method. Statistical significant differences at $p < 0.05$. Designations in Table 1.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Count</th>
<th>Average</th>
<th>Standard Deviation</th>
<th>Coeff. of Variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>F</td>
<td>2</td>
<td>60.325</td>
<td>0.176777</td>
<td>0.03125%</td>
</tr>
<tr>
<td>K</td>
<td>2</td>
<td>68.95</td>
<td>0.636396</td>
<td>0.405%</td>
</tr>
<tr>
<td>M</td>
<td>2</td>
<td>64.23</td>
<td>2.44659</td>
<td>5.9858%</td>
</tr>
<tr>
<td>F-K</td>
<td>2</td>
<td>54.745</td>
<td>0.813173</td>
<td>0.66125%</td>
</tr>
<tr>
<td>F-M</td>
<td>2</td>
<td>57.29</td>
<td>1.47078</td>
<td>2.1632%</td>
</tr>
<tr>
<td>K-F</td>
<td>2</td>
<td>58.16</td>
<td>1.4425</td>
<td>2.0808%</td>
</tr>
<tr>
<td>M-F</td>
<td>2</td>
<td>61.06</td>
<td>0.905097</td>
<td>0.8192%</td>
</tr>
</tbody>
</table>

The effect of the drying method on the porosity of dried carrots was shown in Figure 6. The highest porosity value of 84.14% was obtained in freeze-dried carrots (F). The convective dried sample (K) was characterized by the lowest porosity among all drying methods. The combination of freeze-drying and convective drying (F-K, K-F) allowed us to obtain statistically significant lower porosity of 44.28%, 36.7%, compared to freeze-dried (F) samples but higher than convective dried (K) (Table 6). Differences were statistically significant. The dried material obtained by hybrid (combined) methods with the use of microwaves and freeze-drying (M-F, F-M) had a porosity of 57.16 and 52.06%, respectively, and results were significantly higher than for the microwave-dried (M) 37.38%.

![Figure 6](image_url)

Figure 6. The impact of the type of drying method on the porosity of dried carrots. The same letters (a–g) in individual columns indicate the absence of a statistically significant difference between the samples (significance level 0.05). Designations in Table 1.

Table 6. The results of the analysis of the variance of porosity for dried carrots depend on the drying method. Statistical significant differences at $p < 0.05$. Designations in Table 1.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Count</th>
<th>Average</th>
<th>Standard Deviation</th>
<th>Coeff. of Variation</th>
</tr>
</thead>
<tbody>
<tr>
<td>K-F</td>
<td>3</td>
<td>36.7233</td>
<td>0.546474</td>
<td>1.48808%</td>
</tr>
<tr>
<td>K</td>
<td>3</td>
<td>31.82</td>
<td>0.230651</td>
<td>0.724863%</td>
</tr>
<tr>
<td>F-M</td>
<td>3</td>
<td>57.1533</td>
<td>0.381095</td>
<td>0.666794%</td>
</tr>
<tr>
<td>F</td>
<td>3</td>
<td>84.1433</td>
<td>0.388115</td>
<td>0.461255%</td>
</tr>
<tr>
<td>F-K</td>
<td>3</td>
<td>44.71</td>
<td>0.39281</td>
<td>0.878574%</td>
</tr>
<tr>
<td>M-F</td>
<td>3</td>
<td>52.0233</td>
<td>0.120554</td>
<td>0.231731%</td>
</tr>
<tr>
<td>M</td>
<td>3</td>
<td>37.46</td>
<td>0.383145</td>
<td>1.02281%</td>
</tr>
</tbody>
</table>

The internal structure of dried carrots was examined using a scanning electron microscope (Figure 7). The convective dried carrot tissue (K) (Figure 7A) is characterized by a regular distribution of pores, evenly shaped and of similar sizes, in high-density clusters.
The freeze-dried material (F) (Figure 7C) in the microscopic image is distinguished by a large number of pores of small diameter, creating a delicate porous structure. Compared to the convection (K) (Figure 7A) and microwave (M) (Figure 7F) methods, the structure of the tissue was not exposed to high temperature, the pores are much smaller and there are no numerous damages and structural cracks. Freeze-drying in combination with microwave-drying (F-M) (Figure 7E) made it possible to obtain dried material with an internal structure in which the pores at the surface are regularly distributed, with a high, uniform density, while in the central part there are numerous larger pores with irregular shape.

**Figure 7.** The impact of the type of drying method on the structure of dried carrots. Magnification 10×. (A) Convective-drying (K), (B) Convection–freeze-drying (K-F), (C) Freeze-drying (F), (D) Freeze-drying–convection (F-K), (E) Freeze-drying–microwave (F-M); (F) Microwave-drying (M), (G) Microwave–freeze-drying (M-F). Designations in Table 1.

To obtain a complete picture of the color changes that occurred as a result of drying with various methods compared to the color of raw carrot, the absolute difference in color coefficient was calculated (Figure 8) (Table 7). The lowest value of \( \Delta E \) characterizes the microwave-dried carrot sample (M) 15.52. Carrots subjected to microwave-drying (M) and combined drying using microwaves and freeze-drying (M-F) were the least changed in color, the differences are not statistically significant, and the freeze-dried carrot (F) was the most changed. All the dried samples obtained with the combined methods (K-F), (F-K), (M-F), and (F-M) showed lower values of the tested index than freeze-dried (F), and the differences were statistically significant.
terms of color, the differences are not statistically significant, and the freeze-dried carrot (F) was the most changed. All the dried samples obtained with the combined methods (K-F), (F-K), (M-F), and (F-M) showed lower values of the tested index than freeze-dried (F), and the differences were statistically significant.

Figure 8. The impact of the type of drying method on the absolute difference in color [ΔE] of dried carrots. The same letters (a–e) in individual columns indicate the absence of a statistically significant difference between the samples (significance level 0.05). Designations in Table 1.

Table 7. The results of the analysis of the Tukey test of the absolute difference in color [ΔE] for dried carrots depend on the drying method. Statistical significant differences at $p < 0.05$. Designations in Table 1. The asterisks in the same columns and rows indicate no statistically significant differences between the samples.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Average ΔE</th>
</tr>
</thead>
<tbody>
<tr>
<td>M-F</td>
<td>15.55500</td>
</tr>
<tr>
<td>F-K</td>
<td>16.63000</td>
</tr>
<tr>
<td>K-F</td>
<td>18.51000</td>
</tr>
<tr>
<td>F-M</td>
<td>18.56000</td>
</tr>
<tr>
<td>K</td>
<td>19.16000</td>
</tr>
<tr>
<td>F</td>
<td>19.78000</td>
</tr>
<tr>
<td>M</td>
<td>26.77000</td>
</tr>
</tbody>
</table>

4. Discussion

The state of water in the material is described by the water activity parameter ($a_w$). It ranges from 1 for clean water to 0 for the environment in which no water was found [30]. The value of water activity present in food products is a parameter that determines the stability of food by directly influencing the development of microflora. Literature data indicate that water activity must be below the value of 0.6 to call the material safe, and is assigned to food groups with low water content [31,32]. Based on the presented results, it can be concluded that the water activity of the tested dried carrot for all drying methods was below the value of 0.4, which means that the dried product was safe. The drying process caused the water to evaporate, thanks to which its activity significantly decreased in all samples, regardless of the drying method (0.176–0.390) compared to raw carrots, where the activity was 0.964. The lowest value was characteristic of freeze-dried carrots (0.176). Ciurzyńska et al. [18], examining the influence of drying methods on the quality of dried material, obtained a similar value of $a_w$ for freeze-dried pumpkin. Such a low value of this parameter for dried material is caused by a complicated process including a freezing step and drying under a vacuum. The higher water activity value of samples dried by microwave and convection-drying can be connected with less water removal from the sample, as the material is often baked as a result of microwave and convection-drying.
This happens when the process parameters are not properly selected. Caking the surface of the material prevents the removal of water from the inner layer of the material, which results in a higher water activity compared to other drying methods. For samples dried by hybrid (combined) methods an intermediate $a_w$ value was obtained; however, when it comes to the differences in the duration of the process between freeze-drying–convection and freeze-drying–microwave, freeze-drying with microwave is a more effective method, because its duration was 6 h and 2.5 h, respectively (Table 1). The use of the freeze-drying process as the first stage of drying in hybrid (combined) methods resulted in obtaining the dried carrot that was the closest in terms of water activity to freeze-dried. Relatively, the low water activity of these dried samples results from the fact that in the combined methods of drying, freeze-drying was applied, preceding the actual drying process, or drying to specific water content. The low water activity is because the material subjected to the drying process was previously frozen. The combination of freeze-drying and convection-drying of carrots allowed us to obtain a material with a lower water activity compared to convective-dried. The duration of the process is longer, but not as long as in the case of the freeze-drying itself. It is possible to successfully use this method (freeze-drying–convection) as an alternative to convection and freeze-drying because the obtained dried material has a water activity similar to that of freeze-drying. Inverse results were obtained in drying, in which freeze-drying was used as the last step of drying. In the case of products obtained by these combined drying methods, the water activity value is higher in comparison to methods in which freeze-drying has been used as the first drying step. The results for convective-drying and combined convection–freeze-drying as well as microwave–freeze-drying are similar. The reason for this may be the order of the drying methods used. Microwaves and convection-drying causes the formation of a crust on the surface of the dried material, which hinders the evaporation of water [33].

All dried samples obtained dry matter content exceeding 94%. Similar values (95%) were obtained in the studies by Litvin et al. [34], which concerned the influence of drying methods on the quality of convective-dried carrots. Studies carried out by Witrowa-Rajchert and Rząca [35] on the influence of drying methods on the quality of dried apples showed that the microwave-dried samples obtained a dry matter content of 94.3%. In the presented investigations the highest dry matter content was observed for freeze-dried carrots (~98%). The freeze-drying process is considered to be the best drying method in terms of removing water. The complicated mechanism of this process, as well as the freezing process before drying, caused the water to freeze, thanks to which during drying under reduced pressure, the frozen water, omitting the liquid phase, was transformed into water vapor and removed from the raw material in a quantity higher than in other drying methods [36]. For example, the value of this quality factor for freeze-dried pumpkin in the research conducted by Ciurzyńska et al. [18] was equal to 95.87%. The combination of convection and freeze-drying (K-F; F-K) made it possible to obtain dried material with very similar dry matter content values, 94.11% and 95.68%, respectively, but lower than for freeze-dried samples (F). The freeze-dried carrot with microwave-drying (F-M) is characterized by a similar level of dry matter content to the freeze-dried (F), therefore it can be used as an alternative to freeze-drying and the duration of the process can be reduced.

The apparent density and porosity of plant material have an effect on changes during dehydration due to the loss of moisture and formation of air pores [37]. Apparent density is defined as the result of water, dry matter, and air density [38]. The increase in apparent density in plant tissue causes high shrinkage. The type of raw material also influences the apparent density value. The density of dried products depends on changes in porosity and contraction of the tissue. The more free intercellular spaces, the lower the density of the dried material. Freeze-dried carrots obtained the lowest density, whereas the convective and microwave-dried samples characterized the highest value. Additionally, the combined drying method was less favorable than the freeze-drying method but better than convective and microwave-drying. Chen et al. [39] obtained the lowest value of bulk density for freeze-dried black mulberries and a similar result for samples hybrid dried in freeze-drying.
with explosion puffing drying. The authors explained that in freeze-dried products the frozen water in the material sublimated directly from the solid phase to the gas phase and the porous structure of the samples was well maintained. Nowacka et al. [40] showed that freeze-dried apples had lower density with higher shrinkage. However, in the case of dried carrots, this relationship is not confirmed, which may be related to the difference in the structure and tissue of carrots and apples. A similar relationship was obtained by Lenart et al. [41] for convective-dried carrots and showed that the higher the shrinkage, the greater its density. Hii et al. [3] also indicated that hot air-dried products are often characterized by unattractive physical appearance, excessive shrinkage, and hard texture.

The drying process causes physical changes in the dried material. One of the fundamental but unfavorable changes is shrinkage, which results from the reduction of the volume of the product by the evaporation of a large amount of water. The volume change is accompanied by a change in shape and the amount of evaporated water affects the hardness of the material, therefore the obtained dried material may crack and deform, which adversely affects the final quality of the obtained product. The studies conducted by Hatamipour [42] showed that shrinkage and water content were highly dependent on each other, e.g., the level of shrinkage depends on the water content that is removed during drying. The highest value of shrinkage was characteristic for convection-dried carrots 68.95%. A similar result was obtained by Lenart et al. [41] for carrot convective-dried, and by Dadan and Nowacka [43]. Furthermore, de Souza et al. [44] observed that for carrots convective-dried the shrinkage was the highest, which may be related to the longer drying time, leading to a higher collapse of the cellular structure of the material. In the research of Jałoszyński et al. [45] on the influence of various drying methods, the shrinkage of convection-dried carrots was also the highest. In a convection-dried carrot, the following relationship was observed: the higher the shrinkage, the higher the density, and the lower the porosity. Carrot microwave-dried obtained a similar shrinkage value to convective-dried, which was confirmed by de Souza et al. [44], who explained that it can be attributed to large heat generation and more effective removal of moisture, which can cause damage to the cell structure, and shrinkage. The use of freeze-drying allows for obtaining the dried material with lower shrinkage and better retention of the shape and size of the sample. Combined drying can be used as an alternative to freeze-drying because the shrinkage is similar and the use of combined drying methods allows for a significant reduction in drying time.

Changes in the porosity of plant material are classified as physical changes taking place in the dried material. This parameter describes the number of voids in the material structure. Porosity is defined as the pore volume compared to the volume of the entire material. This parameter plays an important role in the mass transfer process and also determines the mechanical properties and texture of the food. Porosity increases during the drying process and its value are influenced by the type of raw material used [46]. The highest porosity was shown for freeze-dried carrots, while the lowest was for convective-dried. The high porosity in the freeze-dried sample may result from the fact that this material had the lowest water content among other dried samples, which was removed in the greatest amount during freeze-drying, and low shrinkage. Such quality of the product makes it also demanding in terms of storage conditions. The porous structure contributes to the increased absorption of water and water vapor, therefore the freeze-dried material should be stored in conditions of limited access to moisture [47]. The combination of freeze-drying with convection-drying or microwave-drying allows for a lower porosity of the dried material than freeze-drying. Freeze-drying and microwave-drying increased carrot porosity compared to the microwave-dried sample. For microwave-dried carrot water loss, material shrinkage resulted in less porosity.

The results of density, shrinkage, and porosity were confirmed by tissue structure investigations in the microscope. Carrot convection-dried has regularly distributed pores, with similar size and high-density clusters presented which confirm high shrinkage and low porosity value. The freeze-dried carrot is characterized by a large number of small
pores which influence the high porosity of the freeze-dried sample. Delicate conditions of the freeze-drying process affect low damage value in such samples. The high porosity of carrot dried in hybrid drying, freeze-drying and microwave-drying, was confirmed by structure; pores at the surface are regularly distributed, but areas with high, uniform density are visible, while in the central part numerous larger pores with irregular shapes were obtained. In addition, Ambros et al. [48] for hybrid drying of Lactobacillus paracasei F19 using microwave–freeze-drying observed that hybrid drying could produce a more open and porous structure, similar to freeze-dried samples, and this allows instant wetting and effective rehydration.

The color parameter is defined as an indicator of the quality of fresh and processed raw materials. The attractive appearance and color of the product favorably affect the consumer’s senses. The color of a given product depends on the amount and composition of dyes in the product. Carrots are evaluated and often chosen by consumers due to the content of a natural pigment, which is carotene, which determines the characteristic orange color of carrots [49,50]. According to the literature, the ΔE value is an important parameter showing the total color change in dried samples in comparison to raw material [51]. Mokrzycki and Tatol [52] indicate that an inexperienced observer notices the difference in color when $2 < \Delta E < 3.5$; when $3.5 < \Delta E < 5$ a clear difference in color is noticed and when $5 < \Delta E$ the observer notices two different colors. In the range of $0 < \Delta E < 1$, the observer does not notice the difference and in $1 < \Delta E < 2$ only the experienced observer can notice the difference. All dried carrot samples obtained a high value of ΔE coefficient above 15 units so the observer notices two different colors when comparing the dried sample with raw material. It was shown that microwave-dried carrots obtained the lowest value of the absolute difference in color. The lower the value of the ΔE coefficient, the less the sample differs from the standard (raw carrot) [52]. The highest color changes compared to raw carrots were obtained for the freeze-dried sample. Hybrid drying was more favorable than freeze-drying taking into account color changes and microwave-drying with freeze-drying was the best. The drying process as a result of exposure to high temperatures on the material causes changes, e.g., in the structure of the tissue that causes contraction of the material, and a change in porosity. It is important for the color because the porous structure reflects radiation differently during color measurement [53]. Structure changes may be the reason for the highest color changes in freeze-dried carrot which was the most porous and with the highest lightness coefficient. A high value of color changes was obtained for convective-dried carrots, which confirmed Mierzwa et al. [54] for carrots and Kowalski et al. [55] who showed that convective-drying of red bell pepper was a long process and caused a quality decrease. Structure changes were also observed, and color degradation during convective-drying probably was due to enzymatic and non-enzymatic browning reactions; while hybrid drying by combining convective-drying with infrared and microwave had a positive effect on the product quality and drying time. Shrinkage and deformations of samples were smaller, and color was protected. Mierzwa et al. [54] indicated also that for samples microwave dried, the color degradation may result from high temperatures occurring in the material due to microwave radiation. Mierzwa et al. [56] observed similar results for carrots dried in hot air with a microwave. Hybrid drying shows that microwave power should be applied according to the loss of moisture, which influences the microwave absorptivity and thus the drying efficiency, especially towards the end of drying.

5. Conclusions

Combined drying methods, in which freeze-drying was used first, followed by convection or microwave-drying, proved to be alternative techniques that can successfully replace the long and costly freeze-drying process (reducing the processing time by more than 20 h). The product obtained by combined drying methods has high dry matter content, low water activity, and lower shrinkage compared to convection-drying, microwave-drying, and freeze-drying, as well as a more attractive and porous structure. The best method, in terms of limiting the color changes of the dried material compared to the raw material, and
with the shortest drying time, was microwave-drying and combined methods using the freeze-drying process as a drying stage with microwave-drying.

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**References**


